eA*

*physics motivation for an electron-ion collider from a QGP perspective

Strange Quark Matter 2013 Conference
21-27 August, Birmingham, UK

Javier L Albacete
Universidad de Granada & CAFPE
Two proposed facilities:

**Electron-Ion Collider, EIC (RHIC /JLAB)**

- EIC white paper, arXiv:1212.1701
e-conveners: T. Ullrich and Y. Kovchegov

  *Also: Spin and 3D structure of the nucleon*
  
  *Talk by Thomas Burton on tuesday*

**Large Hadron-electron Collider, LHeC (CERN)**

small-x conveners: N. Armesto, B. Cole, P. Newman and A. Stasto

  *Also: Precision QCD, EW physics, new physics at high energy*
  
  *Talk by Paul Newman on tuesday*

**Not covered in this talk:**
Accelarator design and challenges, machine performance, detectors...
OUTLINE

Quark and gluon structure in nuclei: status and open questions
(or why a QGP physicist should care)

e+A measurements: highlights
  - structure functions
  - hard diffraction
  - di-hadron production
  - exclusive vector meson production
  - cold nuclear matter effects
Relevant open questions in HIC addressed by an eA

- Nuclear wave function at small x: nuclear structure functions.
- Particle production at the very beginning: which factorisation in pA/eA?
- How does the system behave as \( \sim \) isotropised so fast? Initial conditions for plasma formation to be studied in pA/eA.
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

- \((A,b,x,Q^2)\)-dependence of nuclear structure
- Initial state fluctuations
- Initial State correlations
- Small-x saturation, nPDF’s, CGC?

- Factorization in eA, pA, AA?
- Initial conditions for isotropization in AA

- Hard Probes: Modification of QCD radiation (“energy loss”) and hadronization (“absorption”) in a nuclear medium
• These uncertainties propagate to the calculation of pretty much any hard process
Uncertainty on quark and gluon structure of the nuclei as reflected by nuclear PDF-parametrizations

$R_{V}^{\text{Pb}}(x,Q^2=1.69\text{ GeV}^2)$

$R_{S}^{\text{Pb}}(x,Q^2=1.69\text{ GeV}^2)$

$R_{G}^{\text{Pb}}(x,Q^2=1.69\text{ GeV}^2)$

- Situation specially dramatic for small-$x$ gluons (where most of the particles produced in a HIC come from)

Constrained by DIS
Constrained by DY
Constrained by sum rules
Assumptions i.c. (=Guessed. Complete absence of empiric constraints)
Small-x = High gluon densities

**Saturation**: At sufficiently small-x
- QCD evolution becomes non-linear
- Particle production becomes non-linear
- QCD stays weakly coupled

- The **Color Glass Condensate** effective theory has emerged as the most solid candidate to approximate QCD in the small-x regime.

- CGC provides a consistent description of data at small-x in a variety of colliding systems: e+p, p+p, p(d)-A, AA. However, alternative descriptions exist in all cases.

- Coherence effects at small-x are essential for the description of HIC data. They appear under different names in the literature: shadowing, percolation, transverse momentum cut-offs in event generators, re-summation of multiple scatterings etc.
Small-x = High gluon densities. Theory open questions

• Does collinear factorization + DGLAP evolution hold to arbitrarily small-x?
  If so, are would one be hiding relevant dynamics in the initial conditions for DGLAP evolution?

• Transition from the saturation to the high-\( p_T \) (leading-twist) regime
  CGC evolution (down in \( x \)) does not contain the DGLAP limit, hence after some evolution (at forward rapidities), \( R_{pA} \) predictions reach unity only at unrealistically large values of \( p_T \)
  how \( R_{pA} \) goes back towards unity at high-\( p_T \)?

• The transition from the saturation regime to confinement
  how does it happen? does the coupling run with \( Q_s \)?
  are classical fields still the right degrees of freedom?
The main source of error in the extraction of medium parameters (e.g. $\eta/s$) is our insufficient understanding of the initial state and its fluctuations.

Initial State models: MC-Event Generators, Glauber, CGC-based approaches etc

• CGC dynamics builds up “initial state” correlations that compete with the hydro interpretation of data.

E.g ridge in pPb
Deep Inelastic Scattering: $e^+A \rightarrow e^+X$

**Experimental Advantages**
- **Precise**: Direct access to parton-level kinematics
- **Clear**: Absence of initial state effects
- **Clean**: No spectator background

**Theoretical Advantages**
- Well understood at (N)NLO accuracy

**Photon virtuality:**
\[ Q^2 = -(k - k')^2 > 0 \]

**Bjorken-x:**
\[ x = \frac{Q^2}{2p \cdot q} \]

- Four orders of magnitude increase in kinematic range over previous DIS experiments
  - LHeC: smaller-x, larger $Q^2$
  - EIC: variety of nuclei

- $\nu$PDFs: $eA$ inclusive
- Four orders of magnitude increase in kinematic range over previous DIS experiments
  - LHeC: smaller-x, larger $Q^2$
  - EIC: variety of nuclei
Inclusive structure functions: F2 and FL

\[ \frac{d^2\sigma^{e+e^-\rightarrow eX}}{dx dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right] \]

- Precision nuclear PDF's: x,Q^2 and A-dependence and flavour decomposition (u,d,s,c,b)
- Possibility to distinguish evolution schemes: DGLAP vs GCG (or others)
- High precision tests of collinear factorization. Simultaneous fit of F2 and FL?
- p-Pb will do a lot here. LHeC/EIC: Better handle of kinematics, systematics, A-coverage

F2 + F2c,b + FL

LHeC

EIC

\[ R_L = \frac{F_L(A F^P_L)}{F^P_L} \]

\[ Q^2 = 2.7 \text{ GeV}^2, x = 10^{-3} \]

stat. errors enlarged (x 5)
sys. uncertainty bar to scale

<table>
<thead>
<tr>
<th>Beam Energies</th>
<th>A/f Ldt</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 on 50 GeV</td>
<td>2 fb^{-1}</td>
</tr>
<tr>
<td>5 on 75 GeV</td>
<td>4 fb^{-1}</td>
</tr>
<tr>
<td>5 on 100 GeV</td>
<td>4 fb^{-1}</td>
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</tbody>
</table>

rcBK

EPS09 (CTEQ)
Hard Diffraction in DIS

- A surprising feature of QCD at HERA (e+p): A proton in its rest frame hit by a 25 TeV electron remains intact 15% of the time
- Mediated by colorless exchange -- "pomeron"
- Nuclei: - Coherent (nucleus intact): b-imaging of nuclei
  - Incoherent (nucleus breakup): Saturation

observable subject to strong non-linear effects even with $Q^2$ values significantly bigger than $Q_s^2$

at HERA the NLO DGLAP description breaks down already at $Q^2 \sim 8$ GeV$^2$

clean and unambiguous signal of saturation
Exclusive vector meson production: $e+A \rightarrow e+A+V$

- Similar to diffraction (b-imaging and saturation)
- Easier and cleaner identification of final state
- Bonus track: Constraint on VM wave functions

transverse momentum dependence

energy dependence

J/ψ @ LHeC

LHeC central values from extrapolating HERA data:

$\sigma = (2.96 \text{ nb}) (W/\text{GeV})^{0.721}$

 Vertical (dotted) lines indicate values of $W_\text{max} = \sqrt{s} = 4E_p$ at the LHeC with $E_p = 7 \text{ TeV}$.
Di-hadron azimuthal correlations: e+A -> e+h1+h2+X

- **CGC prediction:** At small-x, back-to-back correlations strongly suppressed

- Coincidence probability

\[ CP(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} \]

**RHIC d+Au forward data**

- Background subtraction, vicinity to the kinematic limit, K-factors, double parton scattering prevent interpretation as a CGC effect

**Predictions for the EIC**

- EIC stage-II
  - \( p_T^{\text{trigger}} > 2 \text{ GeV/c} \)
  - \( 1 < p_T^{\text{assoc}} < p_T^{\text{trigger}} \)
  - \( |\eta| < 4 \)

- eA - nosat
- eA - sat

**eA colliders:** smoking gun for saturation
Unprecedented v-range

\[ \nu = \frac{Q^2}{2Mx} \]

\( \nu = \text{photon energy} \)  
\( z = \text{fraction taken by the hadron} \)

large \( \nu \) : in-medium parton propagation

- Energy and path-length dependence of partonic energy loss and \( p_T \)-broadening

small \( \nu \) : in-medium hadronization

- (Pre)-hadronic absorption
- Stages of hadronization and their time scales

+ first time access to heavy quarks!
+ Azimuthal modulation of the production rate and of the \( p_T \)-broadening provides access to the color and parton density fluctuations in the nucleus
Jets in e+A

- Large $E_T$ even in $eA$
- Useful for studies of parton dynamics in nuclei and photon and jet structure
- Studies of background subtraction and reconstruction pending

Access to large-x values of the gluon distribution. Complementary to F2 data to constrain nPDF’s
Conclusions

- A high-energy eA collider would be to the QGP program the same as HERA for the pp program at the LHC.

- QGP properties cannot be precisely extracted from data without a proper understanding of the initial state: eA collisions would provide access to a precise picture:
  
  • Unprecedented access to small-x nPDF’s
  • Novel sensitivity to physics beyond standard pQD.
  • High precision test of factorization
  • Transverse scan of the hadron at small-x
  • Detailed information on parton energy loss and hadronization dynamics

- Many more processes and observables still to be investigated

- Many thanks to EIC and LHeC working groups for their input!

Thank you!
Back up slides
Complementarity of pA and eA

- New effects likely to be revealed in tensions between eA and pA, AA, ep (breakdown of factorisation)

Talk by Paul Newman on tuesday
pPb. Moving forward: Testing the evolution

\[ R_{pPb}(y)=0 \]

\[ R_{pPb}(y)=2 \]

\[ R_{pPb}(y)=4 \]

\[ R_{pPb}(y)=6 \]

Preliminary results. JLA-Dumitru-Fujii-Nara

nPDF EPS09 results by P Quiroga

(p_{t}, y_{h}>>0)
**proton**: Well constrained by abundant HERA data

**modelling!**
## EIC: eRHIC, ELIC

### Future Opportunities and Facilities

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>3 He</th>
<th>3 Li</th>
<th>79 Au</th>
<th>197 Au</th>
<th>238 U</th>
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<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>5-20</td>
<td>325</td>
<td>215</td>
<td>130</td>
<td>130</td>
<td></td>
<td></td>
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<tr>
<td><strong>CM energy, GeV</strong></td>
<td>80-161</td>
<td>131</td>
<td>102</td>
<td>102</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of bunches or distance between bunches</strong></td>
<td>74 nsec</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td></td>
<td></td>
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<tr>
<td><strong>Bunch intensity (nucleons), 10^{11)</strong></td>
<td>0.24</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>3.8</td>
<td>32</td>
<td>30</td>
<td>19</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>50</td>
<td>420</td>
<td>390</td>
<td>250</td>
<td>260</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Normalized emittance of hadrons, 95%, mm.mrad</strong></td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Normalized emittance of electrons, rms, mm.mrad</strong></td>
<td>5.8-23</td>
<td>7-35</td>
<td>12-57</td>
<td>12-57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RMS bunch length, cm</strong></td>
<td>0.2</td>
<td>4.9</td>
<td>8.3</td>
<td>8.3</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$\beta^*$, cm</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Luminosity per nucleon, 10^{34} cm^{-2}s^{-1}</strong></td>
<td>1.46</td>
<td>1.39</td>
<td>0.86</td>
<td>0.92</td>
<td></td>
<td></td>
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</tbody>
</table>

### MEIC, polarized

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>$p^-$</th>
<th>Beam</th>
<th>e-beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
<td>749</td>
<td></td>
</tr>
<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td>0.416</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>%</td>
<td>&gt; 70</td>
<td>~ 80</td>
<td></td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-3}$</td>
<td>0.3</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Horiz. emit. (norm.)</td>
<td>$\mu$m</td>
<td>0.35</td>
<td>53.5</td>
<td></td>
</tr>
<tr>
<td>Vertical emit. (norm.)</td>
<td>$\mu$m</td>
<td>0.07</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>Horizontal $\beta^*$</td>
<td>cm</td>
<td>10 (4)</td>
<td>10 (4)</td>
<td></td>
</tr>
<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>2 (0.8)</td>
<td>2 (0.8)</td>
<td></td>
</tr>
<tr>
<td>Vertical beam-beam tunesift</td>
<td></td>
<td>0.015</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Laslett tunesift</td>
<td></td>
<td>0.06</td>
<td>small</td>
<td></td>
</tr>
<tr>
<td>Distance from IP to 1st final focusing quad</td>
<td>m</td>
<td>7 (4.5)</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Luminosity per IP</td>
<td>$10^{33}$cm^{-2}s^{-1}</td>
<td>5.6 (14.2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Kinematics: LHC vs. EIC/LHeC

- **Existing ep**: pp@LHC at \( y = 0 \); eA: not even dAu@RHIC.
- **LHeC**: clean scan of the LHC x-\( Q^2 \) domain.
- **EIC**: complements HERA with eA.